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The increase of soil organic carbon as proposed by the "4/1000 initiative" is strongly limited by the status of soil development - A case study along a substrate age gradient in Central Europe

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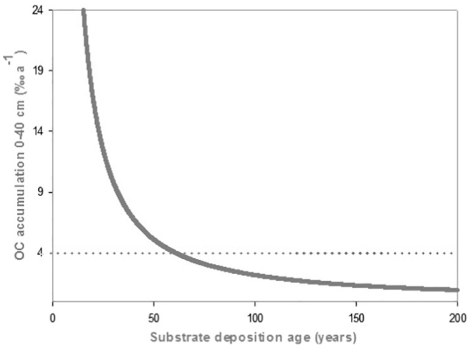
HIGHLIGHTS

- The status of soil development strongly influences the C-accumulation rates in soils.
- After 350 years of soil development, C-sequestration under various land use is highly limited in our study area.
- C-accumulation of more than 4‰ per year was only observed during the first 60 years of soil formation.

GRAPHICAL ABSTRACT



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ABSTRACT

During COP 21 in Paris 2015, several states and organizations agreed on the "4/1000" initiative for food security and climate. This initiative aims to increase world's soil organic carbon (SOC) stocks by 4‰ annually. The influence of soil development status on SOC dynamics is very important but usually not considered in studies. We analyse SOC accumulation under forest, grassland and cropping systems along a soil age gradient (10–17,000 years) to show the influence of soil development status on SOC increase.

SOC stocks (0–40 cm) and accumulation rates along a chronosequence in alluvial soils of the Danube River in the Marchfeld (eastern Austria) were analysed. The analysed Fluvisols and Chernozems have been used as forest, grassland and cropland for decades or hundreds of years.

The results showed that there is a fast build-up of OC stocks (0–40 cm) in young soils with accumulation of ~1.3 t ha^{-1} a^{-1} OC in the first 100 years and ~0.5 t ha^{-1} a^{-1} OC between 100 and 350 years almost independent of land use. Chernozems with a sediment deposition age older than 5.000 years have an accumulation rate $<$ 0.01 t OC ha^{-1} a^{-1} (0–40 cm).

Radiocarbon dating showed that the topsoil (0–10 cm) consists mainly of ">modern" and "modern" carbon indicating a fast carbon cycling. Carbon in subsoil is less exposed to decomposition and OC can be stored at long-time scales in the subsoil (^{14}C age of 3670 ± 35 BP).

In view of the '4/1000' initiative, soils with constant carbon input (forest & grassland) fulfil the intended 4‰ growth rate of SOC stocks only in the first 60 years of soil development. We proclaim that under the present climate in Central Europe, the increase of SOC stocks in soil is strongly affected by the state of soil development.

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1. Introduction

Soil and its organic carbon (OC) content play an important role for food security, in the global carbon cycle and in climate change. Worldwide, soils are the largest terrestrial pool of organic carbon and store about 2500 Pg of C to 2 m depth in the form of soil organic matter (SOM) (Batjes, 1996; Scharlemann et al., 2014; Trumbore, 2009). Due to land use and land cover changes, emissions from terrestrial ecosystems are the second largest anthropogenic source of carbon into the atmosphere (Scharlemann et al., 2014). The loss of SOC from agricultural land is identified as one of the eight major threats to soils (Blum, 2013) as it negatively influences soil fertility and the soil's function of providing ecosystem services (Haddaway et al., 2016). In Europe, a too low SOC content (<1%) in agricultural soil is also one of the most limiting factors for soils to be resilient against negative environmental impacts and to perform on high levels (Schiefer et al., 2016). Such a high resilience and production capacity of soils is the basis for a sustainable intensification as it allows intensive agriculture with high yields but without the massive negative environmental impacts (Buckwell et al., 2014; Schiefer et al., 2015).

The importance of SOC for food security and climate change was also recognised during the United Nations Framework Convention on Climate Change, 21st Conference of the Parties (COP 21) launched in Paris, France, in December 2015. At COP 21 the “4 per mille - Soils for food security and climate” initiative was introduced. This “4 per mille” or “4/1000” initiative seeks to increase global soil carbon in the first 40 cm of agricultural soils by 4‰ annually in the next 25 years (Lal, 2016; Rhodes, 2015). This increase could compensate for the global greenhouse gas emissions and resultant climate change, ensure food security and contribute to the UN sustainable development goals (4pour1000, 2017). To reach this ambitious goal, management strategies such as conservation agriculture, mulch farming, cover cropping, agroforestry, biochar application, improved grazing and/or restoration of degraded soils were suggested (Lal, 2016). However, some studies suggest that a change of management practice cannot prevent ongoing losses of SOC from the topsoil (Steinmann et al., 2016).

For the “4 per 1000” initiative it is also important to maximize the residence time of additional C in soils (Dignac et al., 2017) and to define C saturation levels to identify realisable C-accumulation potentials (Minasny et al., 2017). Studies showed that soils can reach a maximal soil C level showing no response to increasing C inputs due to a carbon saturation in soil (Gulde et al., 2008; Six et al., 2002; Stewart et al., 2008, 2007; West and Six, 2007; Zehetner et al., 2009). Besides the finite capacity of soils to store OC, it must also be considered that the process of carbon storage is reversible (Powlson et al., 2011). Zehetner et al. (2009) showed that along the floodplain soil chronosequence in the Marchfeld, carbon is rapidly accumulated in the first years of soil development and shows equilibrium and stabilization in various humus fractions already within 100 years. Another study showed that a recently developed Mollisol shows a positive non-linear relation between C inputs and SOC stocks. However, the same management does not cause any OC stock increase in mature Mollisols (You et al., 2017).

As a consequence, the main objective of this study is to analyse the influence of the soil development status on the accumulation potential of SOC. To our knowledge, we evaluate the first time for how many years soils show a C-accumulation potential of (more than) 4‰ per year under the actual land use and management practices.

In the Marchfeld region (eastern Austria) soils along a substrate age gradient developed on the same parent material and under the same climate (Zehetner et al., 2009). The soil chronosequence includes the whole Holocene and a maximum sediment deposition age of 17,000 years, whilst the youngest soils have only recently developed on fresh river sediments (<40 years). We analysed the carbon stocks and accumulation rates in the upper 40 cm as proposed by the ‘4/1000’ initiative and performed radiocarbon dating for a better understanding of OC dynamics along the soil chronosequence.

2. Material and methods

2.1. Study area and soil sampling

The study area is located in the Marchfeld, a Danube floodplain downstream of Vienna/Austria (Fig. 1) showing little variation in topography and climate. More information and a detailed description of the study area can be found in Lair et al. (2009a, 2009b, 2009c) and Zehetner et al. (2009). The area is located in a continental climate with a mean annual temperature of ~9 °C and a mean annual precipitation of about 550 mm in the past 30 years. The Marchfeld is situated in the tectonically active Vienna Basin. The formation of the Vienna basin terrace staircase has been controversially discussed, especially with regard to the role of climatic vs. tectonic forcing factors. An overview about this discussion was recently provided by Lüthgens et al. (2017). The study area is strongly influenced by the Danube River which was regulated from 1870 to 1875. From 1882 to 1905 a flood control dike was built (Fig. 1) which disconnects the older part of the floodplain from the Danube River. The land close to the river experiences regular floods. The selected sites (except islands) are located close to the dike, which are only slightly affected by inundations and accompanied sediment input. We analysed soils under conventional agricultural use as well as under semi-natural forest and grassland (mowed once or a year).

The history of land use in the Marchfeld area can be exactly retraced till the late 18th century (Hartmann, 2003). However, the first settlement in this area was very sparse in the Neolithic period. Since the Copper Age a more or less dense population on higher elevations on the border to the Marchfeld can be retraced and since the Middle Ages settlements and agricultural production is documented (pers. comm. University Vienna, Institute of History).

The soil sampling campaigns took place between 2010 and 2014. Soil samples were carefully chosen based on aerial photographs and landscape evaluation. Each study site (Fig. 1) was sampled at least in triplicates at the corners of an equilateral triangle of 10 to 20 m. A fixed-depth interval sampling method (using an 8-cm core drill with a core height of 15 cm from Eijkelkamp Agrisearch Equipment) was combined with a horizontal sampling method (in soil pits) down to a soil depth of 60 to 100 cm, depending on the depth of the AC-horizon.

Soils close to the Danube River experience dynamic conditions that could result in eroded soil profiles. Therefore, all soil profiles were carefully analysed in the field. Soil samples were only taken from profiles with clearly distinguishable A, AC and C horizons and without considerable changes in soil textures.

2.2. Soil characteristics and soil age

All analysed soils developed on Danube sediments of the same parent material. The mineralogy of the river sediments consists of quartz (~35%), calcite and dolomite (~26%), chlorites (5%), Illites/Muscovites (15%), Feldspar (~15%) and Smectites/Vermiculites (~1%). Clay minerals show no transformation along the chronosequence, which can be explained by the carbonate buffered soil system. Regularly floods lead to a deposition of predominantly silt- and fine sand-sized particles at sites within the dike. However, these deposition rates are on average below 0.1 mm per year in the last ten years (pers. Communication, National Park “Donau-Auen”). Older soils outside the dike have a finer texture mainly categorised as loamy silt (Zehetner et al., 2009). The young soils are classified as Fluvisols (within the dike) and show a progressing development to Chernozems with increasing soil age and distance from the Danube.